National Aeronautics and Space Administration

RADIOISOTOPE
POWER SYSTEMS

Radioisotope Power Systems for Outer Planet SmallSats – Enceladus Express Mission Concept

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POWER TO EXPLORE

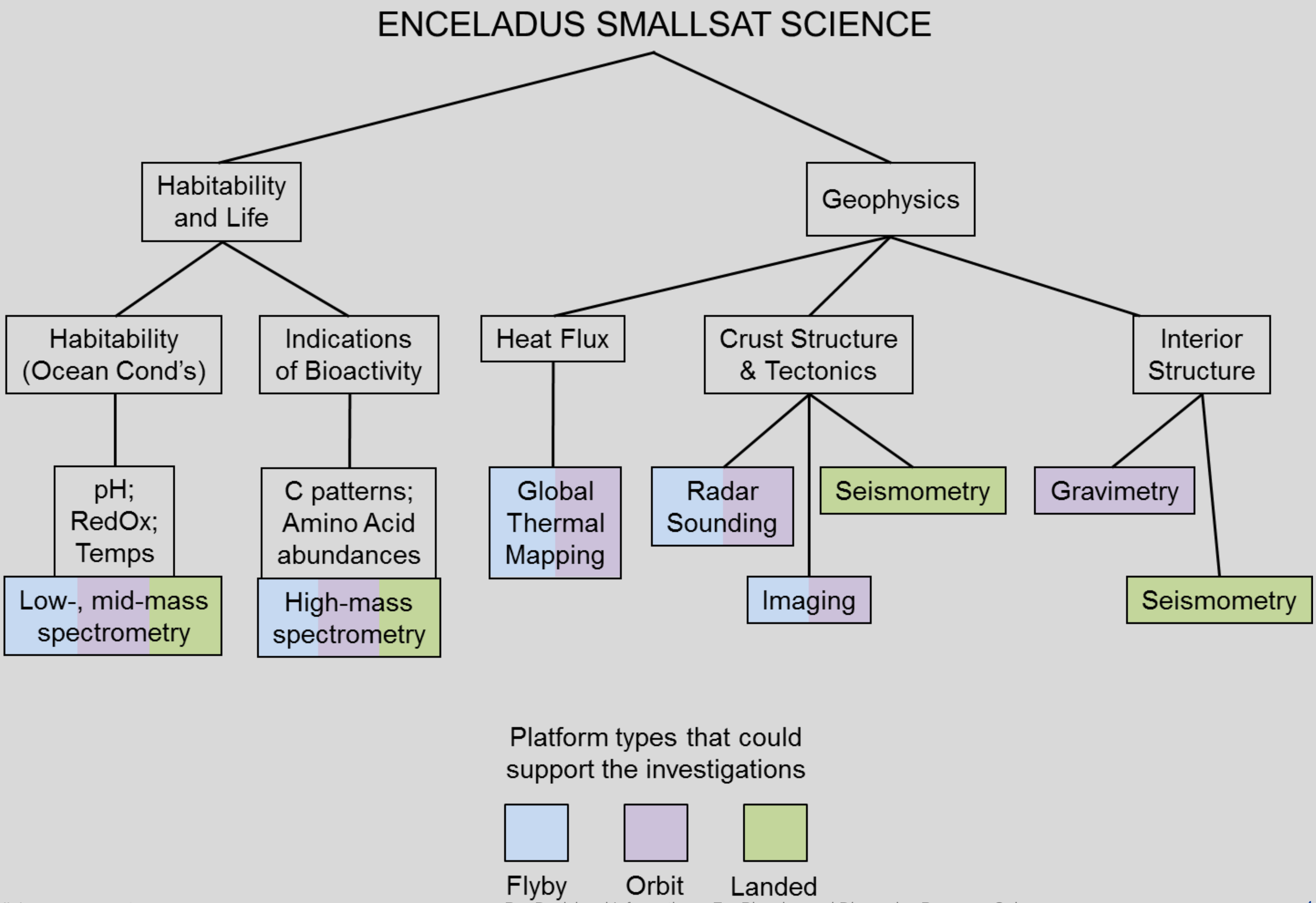
Rationale for RPS SmallSats

- Need for affordable deep space missions
  - NASA and Mission Community strongly desire smaller missions to more destinations for lower cost
- Outer Planets SmallSats
  - Spacecraft in the 100-500 kg mass range could lower mission costs while still performing significant science
  - The challenges of exploration beyond Mars/Jupiter may not be feasible for SmallSats using solar arrays
    - Solar power in the outer solar system could require very large arrays, which in turn could require support from large spacecraft structures.
    - Thermal management in the outer solar system could be prohibitively power-expensive.
- RPS for SmallSats
  - RPS can provide power and heat at any distance from the sun
  - However, the mass and cost of currently available RPS present their own challenges

Enceladus Express - Executive Summary

- The study developed two concepts for Enceladus SmallSats in the 200-400 kg class
  - Enceladus was chosen due to its strong science draw and the applicability of RPS
  - Mission would include two nearly-identical (different only in the instrument payload) SmallSats launched together, each powered by a single MMRTG
  - Targeting NF cost category
- The study concluded that RPS Outer Planets SmallSats are feasible
  - Mission concepts closed mass and power budgets, and were relatively generic designs that could be adapted to other destinations
  - RPS lowers risk for Enceladus plume sampling mission
  - RPS enables aerocapture/gravity assist, which may be an enabling technology for exploring the gas giants with SmallSats

Science Objectives and Investigations



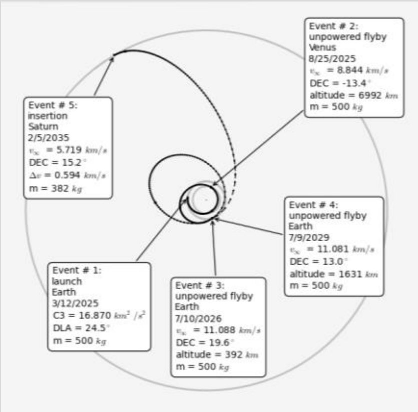
Enceladus Express Concept - Architectures

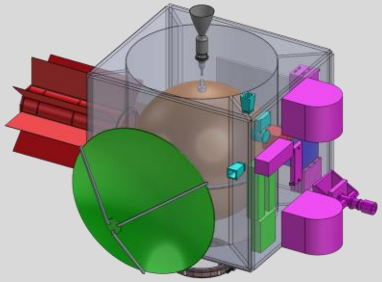
- Case 1: Conventional Chemical Saturn Orbit Insertion
  - 2 Earth and one Venus flybys for gravity assists
  - 1 km/s chemical burn for Saturn Orbit Insertion
  - Saturn close approach will require a close flyby through the ring system, between the F and G rings as Cassini has done

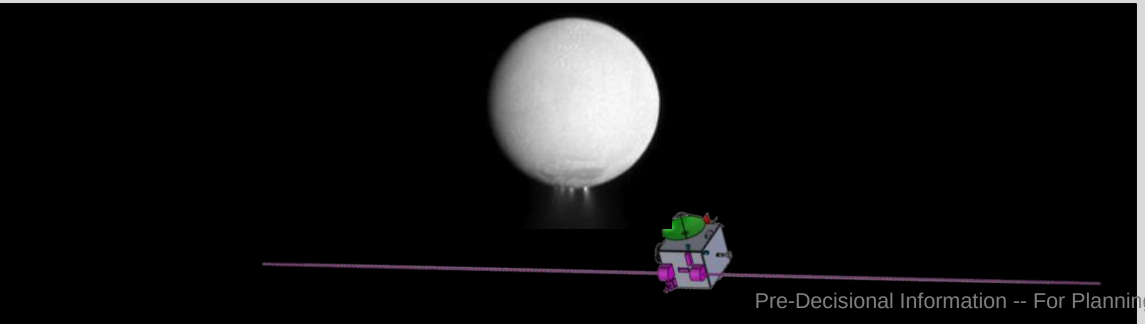
- Case 2: Aerogravity assist at Titan
  - Direct flight to Saturn (requiring a guided upper stage) with upper stage burn (e.g., a Star-48 guided upper stage)
  - Aerobraking and redirection at Titan (same guidance methodology as used by MSL at Mars)
  - Avoids passage through the ring system
  - Transit time shorter by ~2 years

Enceladus Express Concept – Case 1 Summary

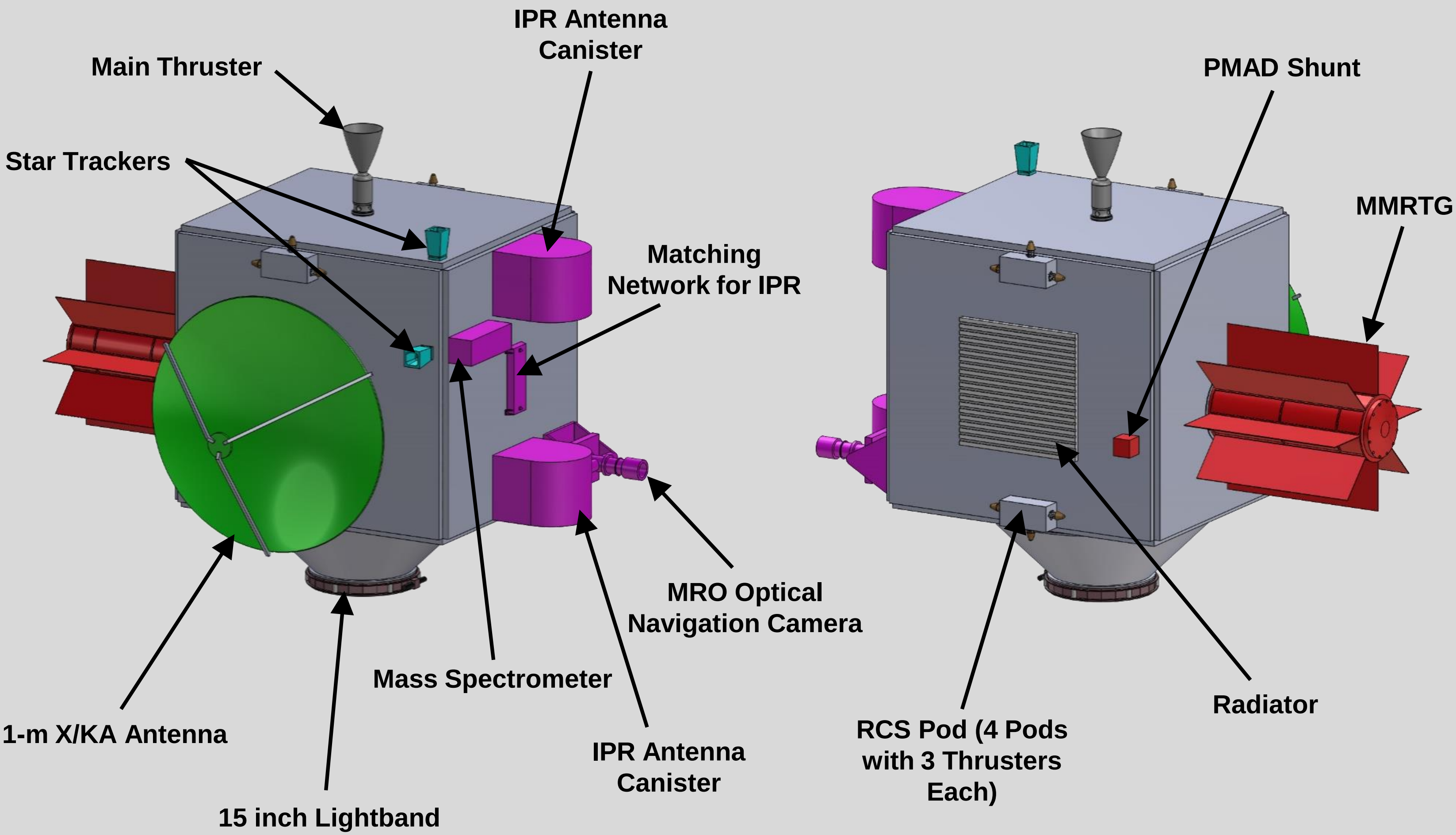
- Mission: Two 450 kg RPS powered SmallSats capture at Saturn and fly through Enceladus plumes 24 times over two years
- Launcher: Atlas 401 to C3 16.8 km^2/s^2
- Science: Habitability and Life, Geoscience(~ 20 kg): Spectrometer, Radar, Imager: 70 Mb (30 Mb compressed) returned every month
- Power (~100W provided by single MMRTG)
  - Single MMRTG sufficient for science and comms (separately) by trickle charging batteries during long, 30 orbits
- Communications - ~ 700 bps Ka-band assuming DSN (34 m)
- AD&CS (IMU, Sun sensors, Startrackers, Cold Gas RCS)
  - Science Collection mode: ~ monthly flyby, 1 hr at a time, 3 axis RCS pointing to 5° accuracy
  - Hibernation during transit: Spun stabilized (3 rpm) pointed to earth
- Propulsion (Hydrazine for all burns)
  - ~ 1 km/s
- C&DH: Radhard Power QUICC, data storage
- Mechanical: Thrust tube design, dual launch platform
- Cost: Dual launch meets New Frontiers cost cap (~ $710M)







Enceladus Express Concept - External Components



Power Requirements

- Single MMRTG would provide power to spacecraft : 118 watts@ BOL with a degradation rate of 4.0%
- During Communication Phase the spacecraft requires 146 watts
- MMRTG is providing 44 watts (after losses to bus)-
  - Deficit of 102 watts
- Strategy – use batteries to provide additional power during high power communication phase and recharge during 30 day orbit
- Worst case (greatest energy storage) occurs during Communication Phase at Year 11
- 30 day orbit period consists of
  - Flyby and data acquisition (~35 w-hr defecit)
  - Short duration recharge for flyby (~60 minutes)
  - 8 hour communication to earth (~560 w-hr deficit)
  - Recharge of Battery (~104 hours -4.33 days)
  - Repeat comm/recharge cycle 1 more times

Case 1 Mission Cost

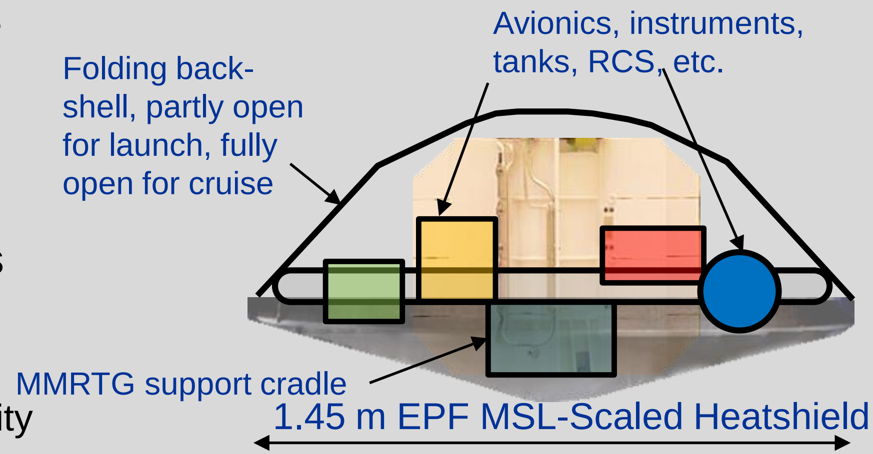
- Total mission cost with 2 SmallSats is within NF Cost Cap
- Uses RPS cost values from the NF 4 AO released on 12/9/2016
- Note this cost is missing Science A-D cost; was not estimated by study

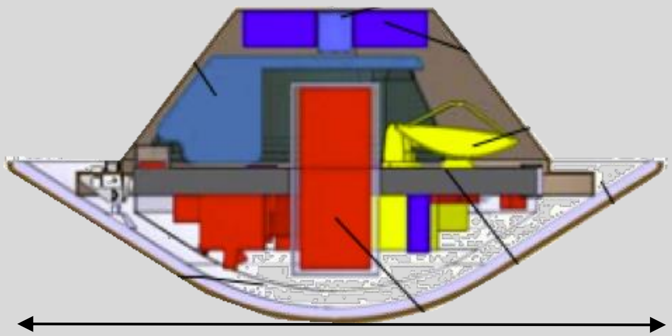
Mission Cost Summary		
		FY 16$M
Phase A		12
1.0	Program Management	38
2.0	Systems Engineering	47
3.0	Safety & Mission Assurance	18
4.0	Science	0
5.0	Payload	89
6.0	Spacecraft	290
6.1	*SmallSat A*	154
6.2	*SmallSat B*	42
6.3	*Total RPS-Related Cost*	94
7.0	Mission Operations (LOOS Only)	12
8.0	Launch Vehicle/Services	13
8.2	*Launch Deck*	13
9.0	Ground System	19
10.0	Systems Integration & Testing	31
11.0	Education & Public Outreach	2
Total Mission Cost		**571**
Reserves (25%)		143
Total Cost with Reserves		**714**

The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

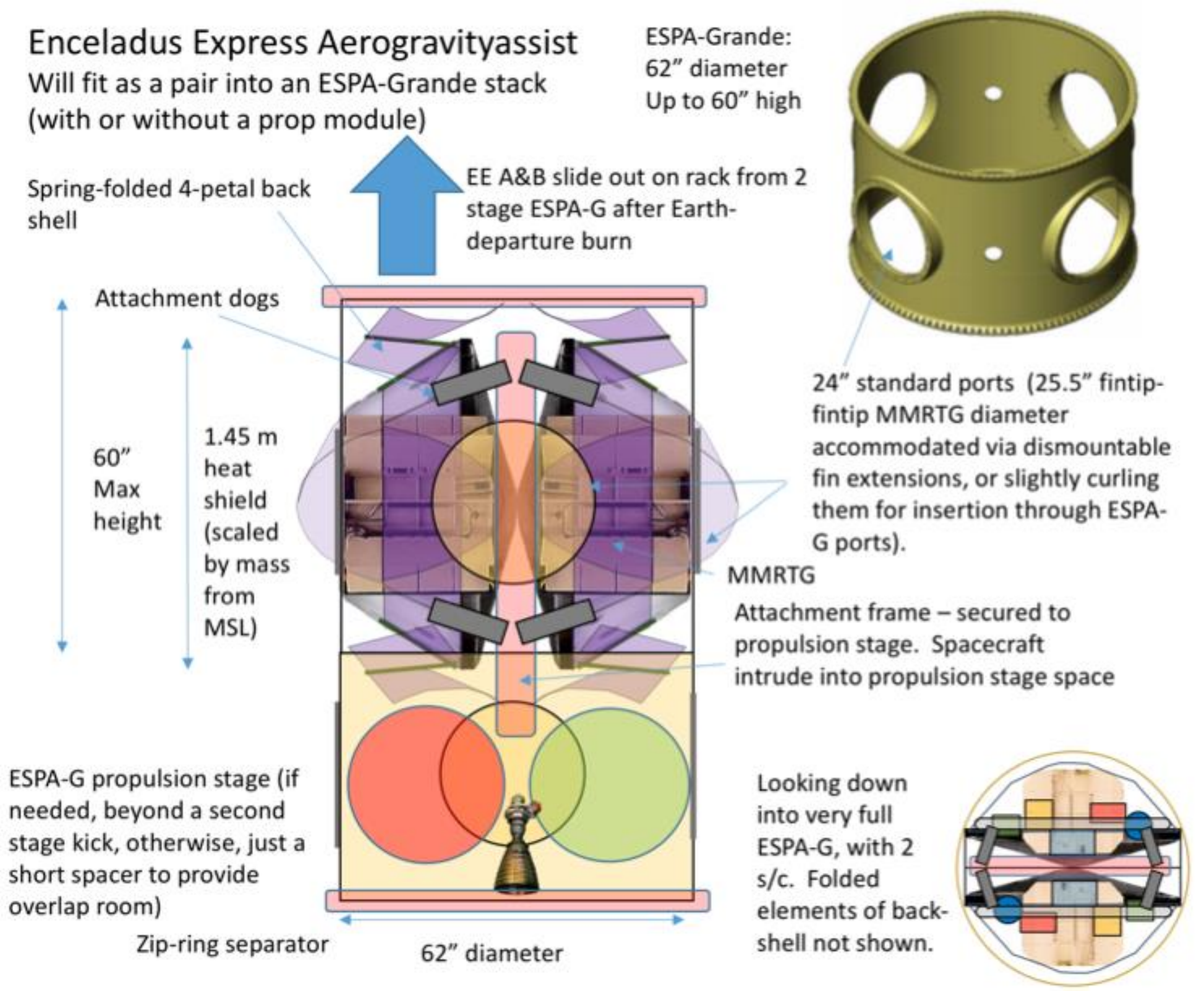
Case 2 Aerogravity Assist Rough Strawman

- Aerocapture: MSL/Huygens-like architecture (using MSL (or HEEET) shell)
- Science: Same as Case 1
- AD&CS: Startrackers look out of back shell
- Propulsion: Same RCS as Case1 (directions may be limited), vastly lower propellant load than Case 1
  - Hole in backshell to fire RCS during aerogravity assist
- C&DH: Added controls for Aeroshell separation and petals and flyby control
- Thermal:
  - Smaller bus than Case 1
  - Added aeroshell and backshell
  - Water cooling using 3-5 kg water (in tank inside S/C ,with pump)
- Mechanical
  - Smaller bus than chemical s/c
  - Spider holding frame to launch platform





Case 2 Launch Configuration

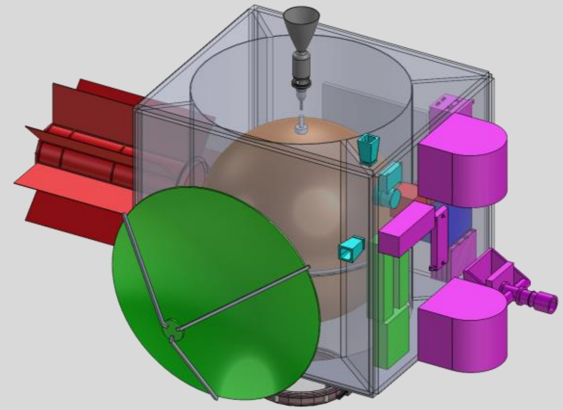


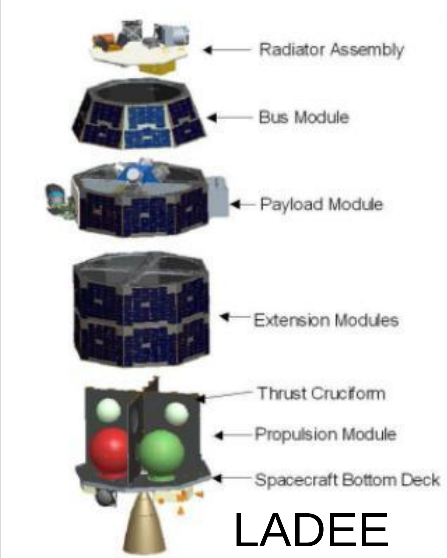
Top-Level Case Comparison

Parameter	Case 1 Monoprop	Case 2 Aerogravity Assist
Launch/Arrival Date	VEEGA 2025/2035	Direct 2026/2031
Launcher	Atlas 401 (w 50% margin): free for NF	Atlas 551/Star 48: Adds $85M
S/C Mass	250 kg dry [~200 kg propellant]	210 kg dry (includes 26 kg aerosystem) [~30 kg propellant]
Mission Cost	~$710M	~$830M
Readiness	Off-the-shelf	Aerogravity assist system needs adaptation from Mars case
Operations	11 year cruise / 2 yr science (~$20M add'l cruise cost)	5 year cruise / 1 yr science
Science Complete	2038	2036
Pros	Lower cost	Much shorter cruise and science phase, 2 year earlier science.
Cons	Longer cruise/ops (13 yrs), 2 year later science, Earth flybys (w/ RPS), Risky Saturn flyby (inside rings)	More expensive launcher, aerogravity maneuver (same as MSL), more complex/expensive S/C with aerosystem?

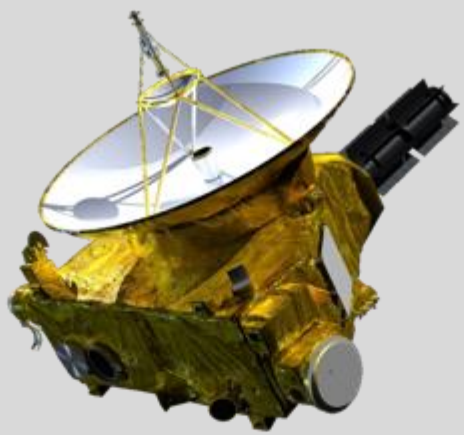
Comparison with Past ‘Small’ Interplanetary Spacecraft

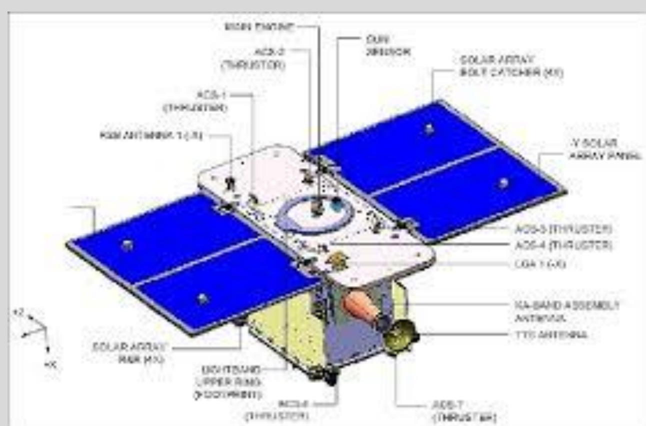
- New Horizons (~$700M): Wet 478 kg / Dry 401 kg / MonoProp 77 kg Payload 30 kg / 200 W_e power @ 9 years (LV: Atlas 551 with a Star48)
- Grail (~$500M): 2 spacecraft each Wet 307 kg/ Dry 201 kg/ MonoPropellant 106 kg / 700 W_e power
- LADEE ($280M): Wet 383 kg / Dry 248 kg / Payload 20 kg / 135kg Propellant (biprop) / ~100 W_e power
- Enceladus Express Case 1 (~$700M): 2 spacecraft each Wet ~450 kg / Dry ~250 kg / ~100 W_e power
- Enceladus Express Case 2 (~$800M): 2 spacecraft each Wet ~250 kg / Dry ~200 kg / ~100 W_e power


Enceladus Express



LADEE


New Horizons


Grail

Technical and Cost Lessons Learned (1)

- A single MMRTG does have sufficient power for a SmallSat IF major events (<day) (science, propulsion, communications) can be supplemented using trickle charged battery power (charged during long periods of non-events ~ 10s of days)
  - Enabled by the Spacecraft 'low-power' mode
- A single MMRTG powered spacecraft, even carrying significant ΔV (~ 1 km/s) and 20 kg of science instrumentation, fits in the SmallSat class (<500 kg)
- Launching two identical, zero fault-tolerant spacecraft provides a method of risk reduction for flybys through Enceladus' plumes
  - An alternative approach using two MMRTGs on one single fault-tolerant spacecraft may or may not provide a cheaper alternative – further work is needed
  - However, a larger dual-string s/c would no longer be a strawman SmallSat solution for other missions

Technical and Cost Lessons Learned (2)

- An approach using aerogravity assist can reduce propellant mass dramatically on the SmallSat but requires an aeroshell system and added risks
  - Aerogravity assist vehicle also delivers science ~1-2 years earlier but costs more, costs that are at least in part compensated by a much reduced mission length
  - This analysis needs further refinement

Study RPS Findings

- RPS SmallSats of 250-500 kg were shown to be feasible.
  - MMRTG can meet the requirements for the mission profile during its 11 year duration
- Spacecraft had EOM power needs of 33 W_e in low-power recharge mode.
  - Small variations in minimum power phase (i.e battery recharge) can lead to greatly increased recharge time
  - Increasing min spacecraft power to 41 W_e prevents power system from closing
- The designed SmallSat concepts were constrained in both mass and power.
  - Mass, dimensions, and cost of the power system pushed the design away from CubeSat to larger, traditional spacecraft components.
  - The high propellant masses and large tank for conventional propulsion made a spacecraft design centered around the MMRTG impractical.
- Use of advanced, smaller RPS could make these mission concepts more compelling since the mass and power degradation of MMRTG became a challenge.
  - If the MMRTG degradation rate is increased from 4% to 5%, the mission doesn’t close
  - Higher power would enable higher data return, and lower risk in low power modes
- An REP architecture was investigated, but study determined that spacecraft could not produce enough thrust for EP with one MMRTG
  - REP, if feasible, could lead to lower propellant mass, smaller propellant tanks, and a smaller spacecraft bus

Conclusions

- Currently available RPS systems (MMRTGs) and their potential improved version (eMMRTGS) are potentially enabling for a wide range of very aggressive but yet economical SmallSat science missions into the outer solar system
  - *As a result, mission designers today can propose small, economical but scientifically important science missions that would be otherwise impossible without RPS*

- Enceladus was chosen as a study target because of its very intriguing internal dynamics that are incongruously and mysteriously keeping an internal ocean active and even venting liquid water – offering the opportunity to test for life processes without landing
  - RPS would keep an Enceladus mission small and lightweight, able to traverse the plumes with low risk compared to solar-powered missions
  - The mission design is applicable as a generic platform for a wider range of outer planets SmallSats
  - Two forms of this mission were studied, a conventional SOI mission (Case 1), and a lower mass aerogravity assist option (Case 2)
  - If Atlas is unavailable, the Falcon Heavy could economically carry both of these cases on ESPA-Grande accommodation
    - For Case 2 (aerogravity assist), the spacecraft could fit inside the adapter ring
  - Both cases potentially fit into the NF cost cap

- Substantial improved performance of current RPS with similar or less mass but higher specific power could enable an REP version of the Enceladus Express SmallSat mission concept, but with a lower spacecraft mass (e.g. 100-200 kg fully loaded)
  - Such a spacecraft would have powerful applicability to a wide range of outer Solar System missions

Questions?